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(HBCU) Development and Application of a Biologically Inspired Methodology for the Optimized, Multi-Disciplinary and Multi-Objective Design of Air Vehicles

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May 2013
Final Report

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14. ABSTRACT

The main accomplishments of this project are:
I. The development and testing of an MOO methodology for multiply-connected domains and its application to concurrent optimization of
sub-system placement and strutural topology;
2. Use of control laws and morphogenesis modell ing for topology optimization; and
3. Application of the methodology developed to simultaneous optimization of an MA V compliant flapping mechanism and wing topology for a
MA V in flapping wing configuration

15. SUBJECT TERMS

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(HBCU) Development and Application of a Biologically Inspired Methodology for the Optimized, Multi-Disciplinary and Multi-Objective Design of Air Vehicles

Final Performance Report
AFOSR Grant FA9550-10-1-0036

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February 27, 2013

§1. OBJECTIVES

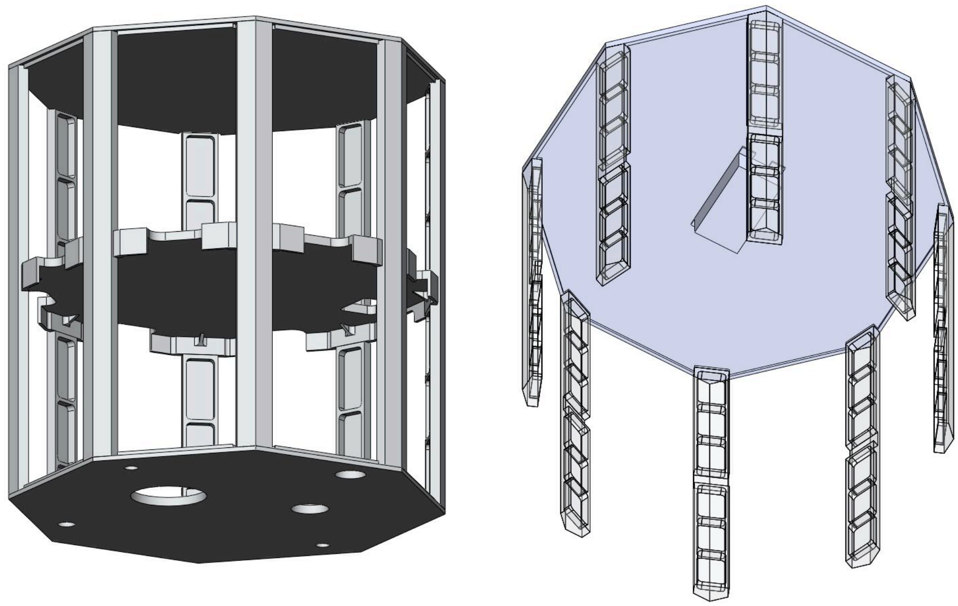
The primary objective of this work was the development and application of a biologically inspired multi-disciplinary design optimization methodology for bridging the chasm between the conceptual design and the detailed design phases.

§2. MAIN ACCOMPLISHMENTS

1. Concurrent Sub-System Placement and Topology Optimization In this project we developed a methodology that can simultaneously optimize the sub-system placement and the topology of the structure around it. To the best of our knowledge, this is the first methodology to accomplish this goal. The results of the methodology applied to optimize the mass of a structural component for a satellite under idealized launch conditions illustrate the methodology.

1. Satellite Panel Design

The structural component to be optimized is shown in figure 1 as well as the subsystem in place. This structural component is designated as the *nominal zenith deck* or simply the *top deck*. The panel (or deck) is part of the satellite structure and is connected to 8 ribs for structural support. The subsystem in this case is an Inertial Measurement Unit (IMU).



((a)) deck is represented at the top of this figure

((b)) top deck, the ribs and the subsystem with transparency seen from “bellow”

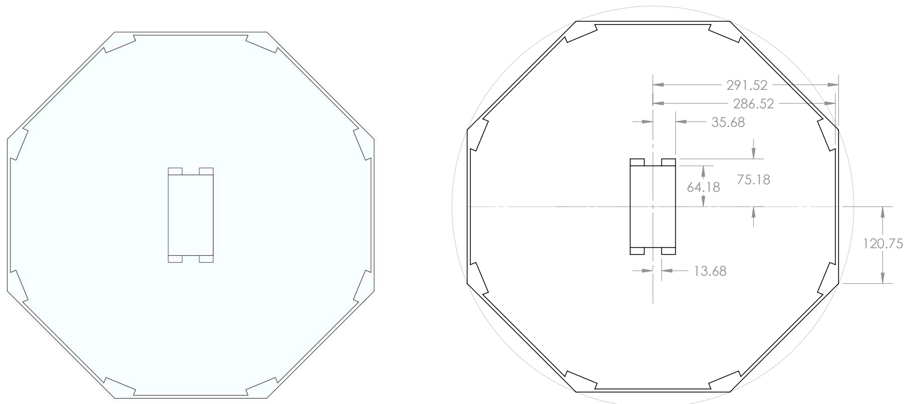
Figure 1: Structural Frame of the HawaiiSat-1

The geometry of the deck is shown in figure 2. This geometry consists of an octagon with an internal rectangular area whose structural elements cannot cross. The top deck will be structurally optimized to minimize its mass while keeping the structural constraints which are given from the structural requirements for the satellite. The maximum displacement of the shell is to be 1 mm. Using a safety factor of 1.5 this requirement is changed to 0.5 mm (or 500 μm) of maximum displacement. The stresses should be within the allowable range, that is, bellow the yield stress of the material to be used. In this case the material used is the Aluminum Alloy 6061-T6 that is known to have high strength and good workability. This alloy has an yield strength of at least 241 MPa and an ultimate tensile strength of 290 MPa[1]. Using the same safety factor of 1.5 we get a yield of 120.5 MPa. Table 1 has the material properties for this alloy.

The design parameters for this work are: parameters (topology); plate thickness for the subsystem region; plate thickness for the main region of the panel; the side length of the external beams; and the side length of the internal beams and the sub-system placement. The boundary conditions are defined to have the eight vertices of the initial map (the octagon) fixed and the boundary edges are free.

There are essentially two structural types used in the panel: the shell and the beams. The

[1]other typical values are 275 MPa for the yield strength and 310 MPa for tensile strength but these were not used in the optimization runs in COMSOL



((a)) panel topology ((b)) panel dimensions in mm

Figure 2: Geometry of the panel

	Aluminum 6061-T6
Young Modulus [GPa]	68.9
Poisson Ratio	0.33
Density [kgm^{-3}]	2700
Shear Modulus [MPa]	25.84
Yield Strength [MPa]	241

Table 1: Material Properties of the Satellite Structure

shell can be divided in two segments, the one called the *main shell* that is the main structural support of the panel excluding the subsystem component, and the other is the subsystem component itself - also referred as the *subsystem shell* whose thickness can be different from the *main shell*. All components of the panel are built with the same material.

The beams are placed on top of the *main shell* and their placement is dependent on the map generation algorithm, which in turn is dependent on the genes. Figure 3 shows an example of the development stages for the map generation algorithm for this panel. The beams are divided in two categories, the internal beams and the external beams. The internal beams are all the newly created beams during the topology development process and the external beams are the ones that define the original map. All beams will have a square cross section but this section may differ according to the side length of the beams.

The analysis is done using the software for topology optimization developed for this work and is written in MATLAB and COMSOLscripting languages. The scripts uses a set of global physical constants that are presented in table 2. It is important to note that these constants are used as the physical setting of this specific problem. There is another set if important global constants that determine the division criteria. These are the minimum length of the edges, defined to be 2% of the characteristic length of the panel (that is

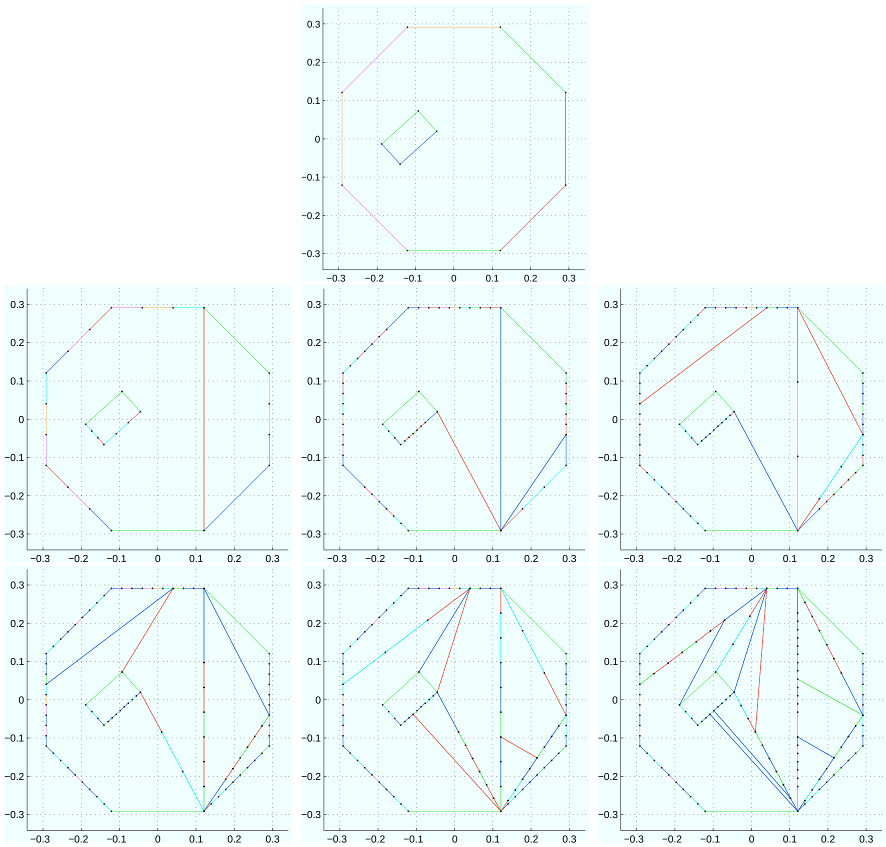


Figure 3: Example of the first 6 steps of the cellular division process using the Map L System for the zenith deck of the HawaiiSat-1

approximately 0.6 m) and the minimum area possible for a cell that is defined to be 2% of the characteristic area of the panel (that is approximately 0.28 m^2) and the minimum angle is set to be 10 deg to avoid sharp angles when creating the mesh in the FE method. A change in these values might lead to different results than those presented in this work.

2. Optimization Run

Several optimization runs were undertaken with a population of two hundred individuals and for one hundred generations, the equivalent to 20,000 individuals were evaluated. Table 3 lists a sample of the the results of the optimization runs using a reference mass of 9.0 kg for the fitness calculation. The stress levels obtained are much smaller than the yield stress for this alloy which makes it a non-critical criteria so the displacement becomes a more important criteria to follow. For more details refer to the figures 4, 5 and 6. These figures show the evolution of the various topologies for the different optimization runs.

constants	value	description
g	9.80665	gravitic acceleration in m^2/s
$area_{panel}$	0.281605	static area of the planar panel in m^2
$area_{IMU}$	0.009158	static area of the planar IMU in m^2
$length_{edge}$	0.2415	length of the side edges in m^2
$mass_{IMU}$	0.299	mass of the IMU in kg
$load_z$	-10.00	vertical load in g
$load_x$	8.75	lateral load in g

Table 2: global constants used in the program that represent physical terms

Run #	Indiv.	Gen.	Run Time	Fitness	Mass [kg]	Mass Reduction (Bench #1)
1 (free)	100	50	43h 51m	0.1604	1.443	85%
2 (fixed)	200	50	38h 17m	0.1813	1.632	83%
3.1 (free)	200	50	33h 03m	0.1459	1.308	86%
3.2 (free)	200	50	25h 15m	0.1422	1.280	87%

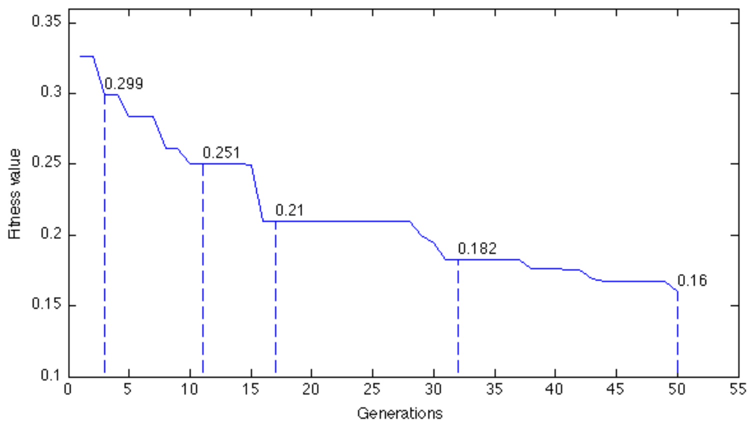
Table 3: Different optimization runs with the Genetic Algorithm based on the biologically inspired methodology for topology generation

The results show the lowest mass to be 1.280 kg. This is a significant improvement when compared to the reference uniform thickness plate.

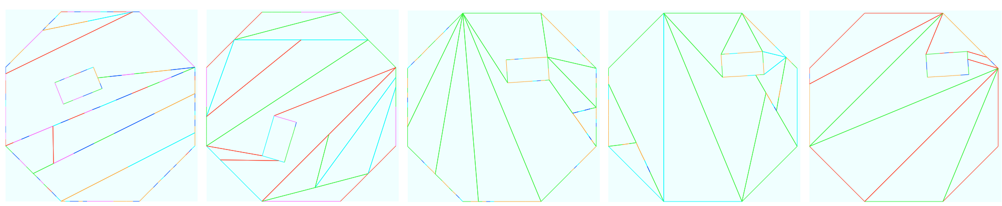
Figures 8 to 11 show the optimum layouts. To validate the beam/plate model, an *a posteriori*, three dimensional model using SolidWorks was setup and run for the best structure. The result is shown in figure 7. The three-dimensional SolidWorks model has a mass of 1.202 kg which is close (within 6%) to the mass obtained with the beam/plate model. The displacement and the stress values are also compared in table 4 and shows again good agreement between the surrogate beam/plate model and the full three dimensional model. The mass and the displacement results between SolidWorks and COMSOL are also close, confirming the accuracy of the model implemented in the software developed. The stress values shows greater differences, but they are still well bellow the yield strength of the selected material.

	mass [kg]	Max. Displacement [μm]	Max. Stress [MPa]
COMSOL→	1.280	473.28	33.6
SolidWorks→	1.202	461.91	42.2
absolute difference	6%	2%	26%

Table 4: Comparison between results from COMSOL and SolidWorks for the most optimized structure.



((a)) Plot with fitness values for the different generations in the run #1.



((b)) Topologies that correspond to the selected fitness values in the fitness plot above.

Figure 4: Topology selection sequencing for run #1.

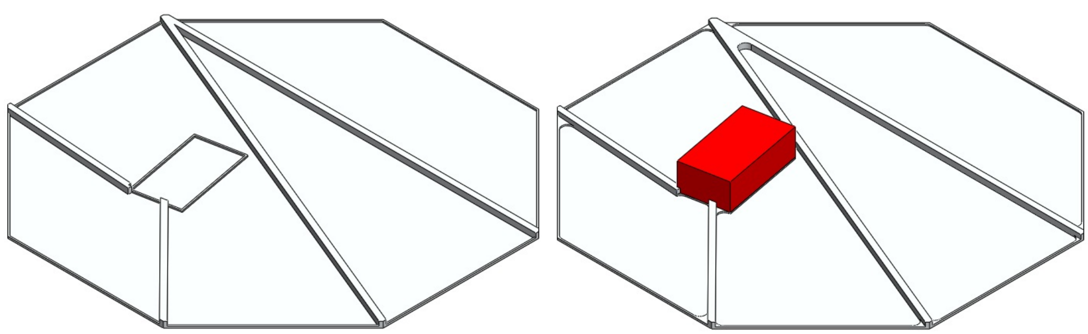
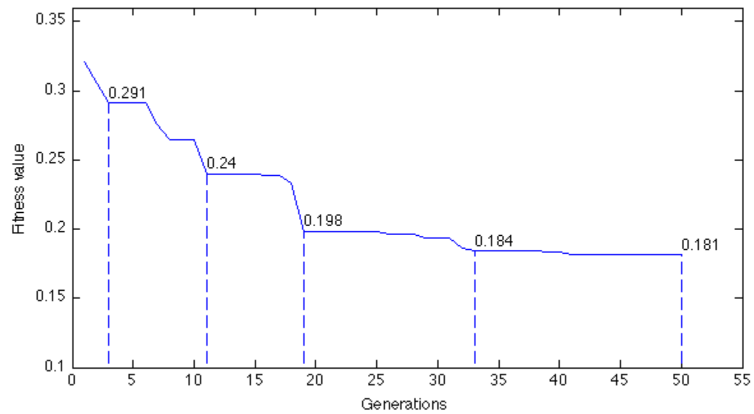
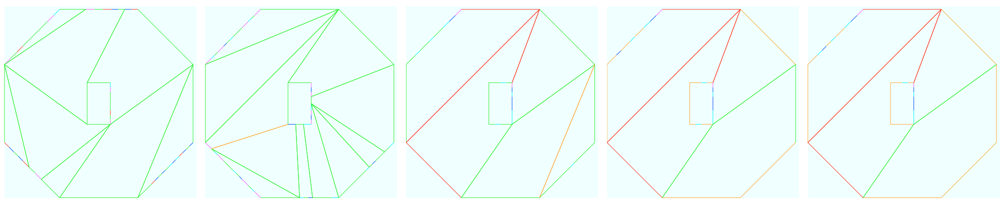


Figure 7: SolidWorks model for the best individual. Raw model on the left and finalized model with chamfers on the right.



((a)) Plot with fitness values for the different generations in the run #2.



((b)) Topologies that correspond to the selected fitness values in the fitness plot above.

Figure 5: Topology selection sequencing for run #2.

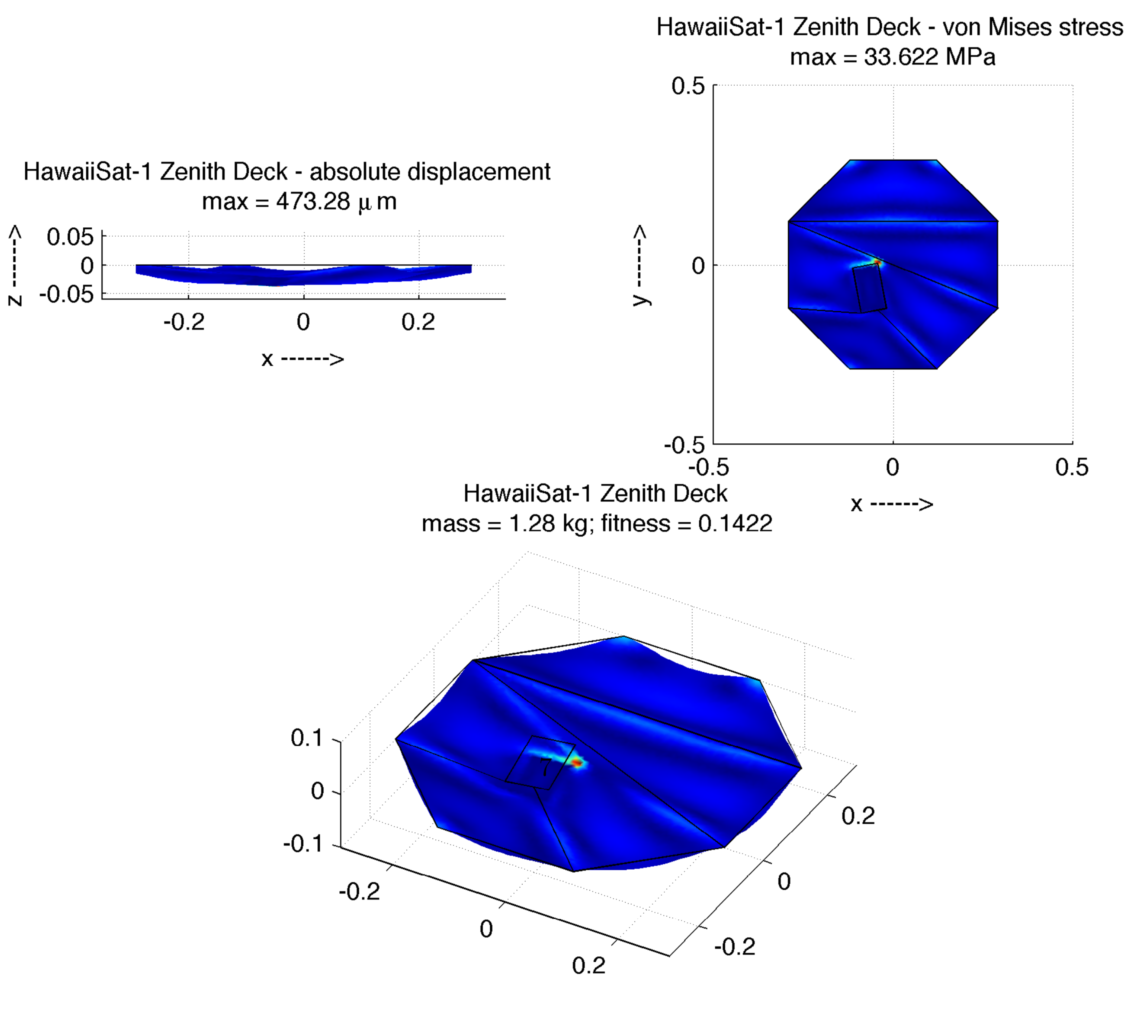
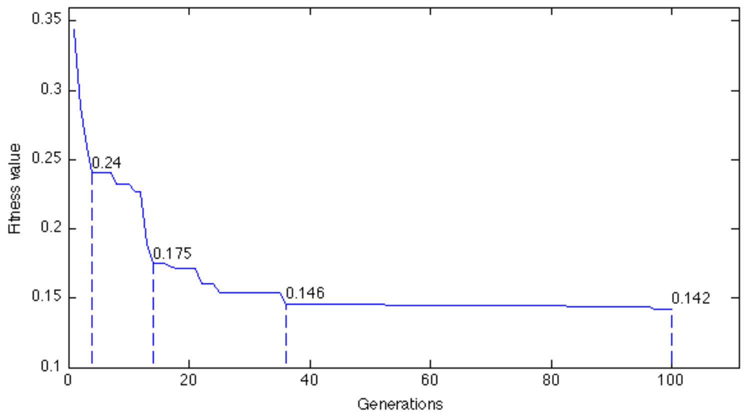
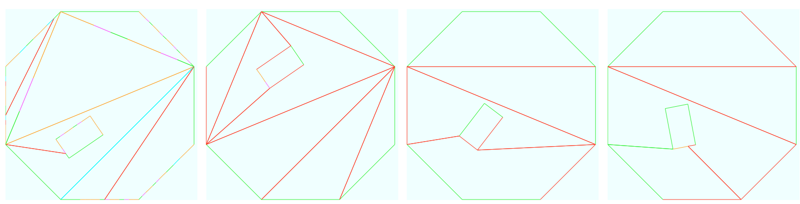


Figure 11: Optimized structure after run #3.2 with 50 generations and 200 individuals starting from best individual in run#3.1. Final Mass = 1.280 kg, Fitness = 0.1422, and subsystem was free to move. This is the best structural topology found.



((a)) Plot with fitness values for the different generations in the run #3.



((b)) Topologies that correspond to the selected fitness values in the fitness plot above.

Figure 6: Topology selection sequencing for run #3.

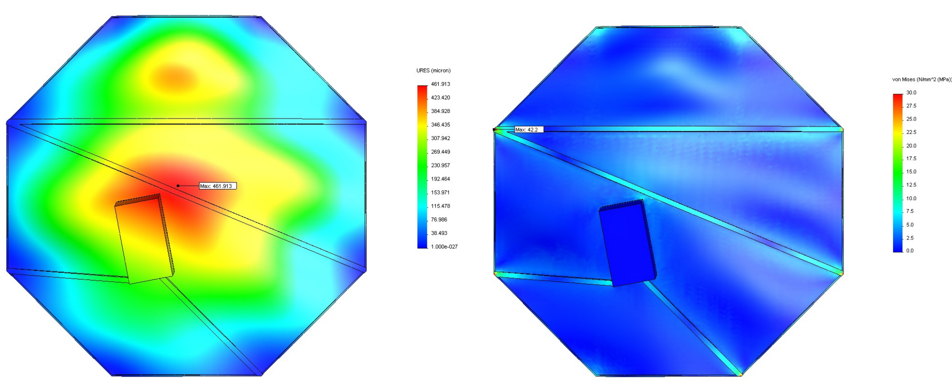


Figure 12: Best optimized structure after run #3 modelled in SolidWorks. Mass = 1.202 kg, Disp = 461.9μm, von Mises Stress = 42.2 MPa.

2. MAV Design

The design of MAVs using the methodology allowed for integrated designs of wing topology integrated with simultaneous optimization of a compliant flapping mechanism to actuate the wing. To the best of our knowledge, this is the first time that this integrated optimization has been performed. Details of the computations can be found in the following papers:

(a) B. K. Stanford, P. S. Beran and M. H. Kobayashi (2013) "Simultaneous Topology Optimization of Membrane Wings and Their Compliant Flapping Mechanism" to appear in the AIAA Journal.

(b) B. K. Stanford, P. S. Beran and M. H. Kobayashi (2012) "Aeroelastic Optimization of Flapping Wing Venation: A Cellular Division Approach" AIAA Journal (50) 938951. DOI: 10.2514/1.J051443.

3. Control Laws for Topology Optimization

Besides the cellular division approach presented above, two other bio-inspired method have been pursed in this work. Both based on the morphogenesis using control laws. This work has originated a paper and a M.Sc. thesis. A second paper based on the results obtained in the M.Sc. thesis is currently under preparation. The paper and the M.Sc. thesis are the following:

(a) M. Chyba, M. H. Kobayashi, F. Mercier, J. Rader, G. Telleschi and A. Tamura-Sato (2011) "A new Approach to Modeling Morphogenesis Using Control Theory" Sao Paulo Journal of Mathematical Sciences (5) 281315.

(b) N. Y. Kawabata, M.Sc., University of Hawaii at Manoa, "A Biologically Inspired Methodology for Multi-Disciplinary Topology Optimization", Spring 2012, advisor: M.H. Kobayashi. Thesis available from UHM library.

§3. PERSONNEL SUPPORTED

The grant supported the following personnel:

Faculty

1. M. H. Kobayashi, PI, Professor of Mechanical Engineering, University of Hawaii at Manoa.

Graduate Students

2. A. Kearney, Ph. D., University of Hawaii at Manoa, All But Dissertation: defense scheduled to Summer 2013, advisor: M.H. Kobayashi.

3. H.T.C. Pedro: Ph.D. University of Hawaii at Manoa, "On Biologically Inspired Designs and Methods" Summer 2010, advisor: M.H. Kobayashi. Dissertation available from UHM library.

4. N. Y. Kawabata, M.Sc., University of Hawaii at Manoa, "A Biologically Inspired Methodology for Multi-Disciplinary Topology Optimization", Spring 2012, advisor: M.H. Kobayashi. Thesis available from UHM library.

Research Experience for Undergraduate Students

1. C. Cruz (University of Puerto Rico), advisor: M.H. Kobayashi.
2. A. Imada (Wellesley College), advisor: M.H. Kobayashi.

In addition to the students supported by the grant, the following students were involved with the research conducted in the project:

Graduate Students

1. M.A. Nunes, M.Sc., University of Hawaii at Manoa, "A Biologically Inspired Methodology for Aerospace Vehicles Design", Summer 2010, advisor: M.H. Kobayashi. Work partially funded by LEONIDAS project. Thesis available from UHM library.

Research Experience for Undergraduate Students

1. I. Patrikeeva (Rice University). Work funded by a REU-NSF grant.
2. M. Coloma (UHM), advisor: M.H. Kobayashi. Work funded by McNair Student Achievement Program at UHM.
3. T. Martinez (UHM), advisor: M.H. Kobayashi. Work funded by McNair Student Achievement Program at UHM.

§4. PUBLICATIONS

The following publications acknowledge the support of this grant:

Journal

1. B. K. Stanford, P. S. Beran and M. H. Kobayashi (2013) "Simultaneous Topology Optimization of Membrane Wings and Their Compliant Flapping Mechanism" to appear in the AIAA Journal.
2. E. Sabbatini, G.M. Revel and M.H. Kobayashi (2013) "Vibration Reduction Using Biologically Inspired Topology Optimization Method: Optimal Stiffeners Distribution on an Acoustically Excited Plate" to appear in the Journal of Vibration and Control.
3. B. K. Stanford, P. S. Beran and M. H. Kobayashi (2012) "Aeroelastic Optimization of Flapping Wing Venation: A Cellular Division Approach" AIAA Journal (50) 938951. DOI: 10.2514/1.J051443.
4. M. Chyba, M. H. Kobayashi, F. Mercier, J. Rader, G. Telleschi and A. Tamura-Sato (2011) "A new Approach to Modeling Morphogenesis Using Control Theory" Sao Paulo Journal of Mathematical Sciences (5) 281315.
5. H. T. C. Pedro and M. H. Kobayashi (2011) "On a cellular division method for topology optimization" International Journal of Numerical Methods in Engineering (88) 11751197. DOI:10.1002/nme.3218.

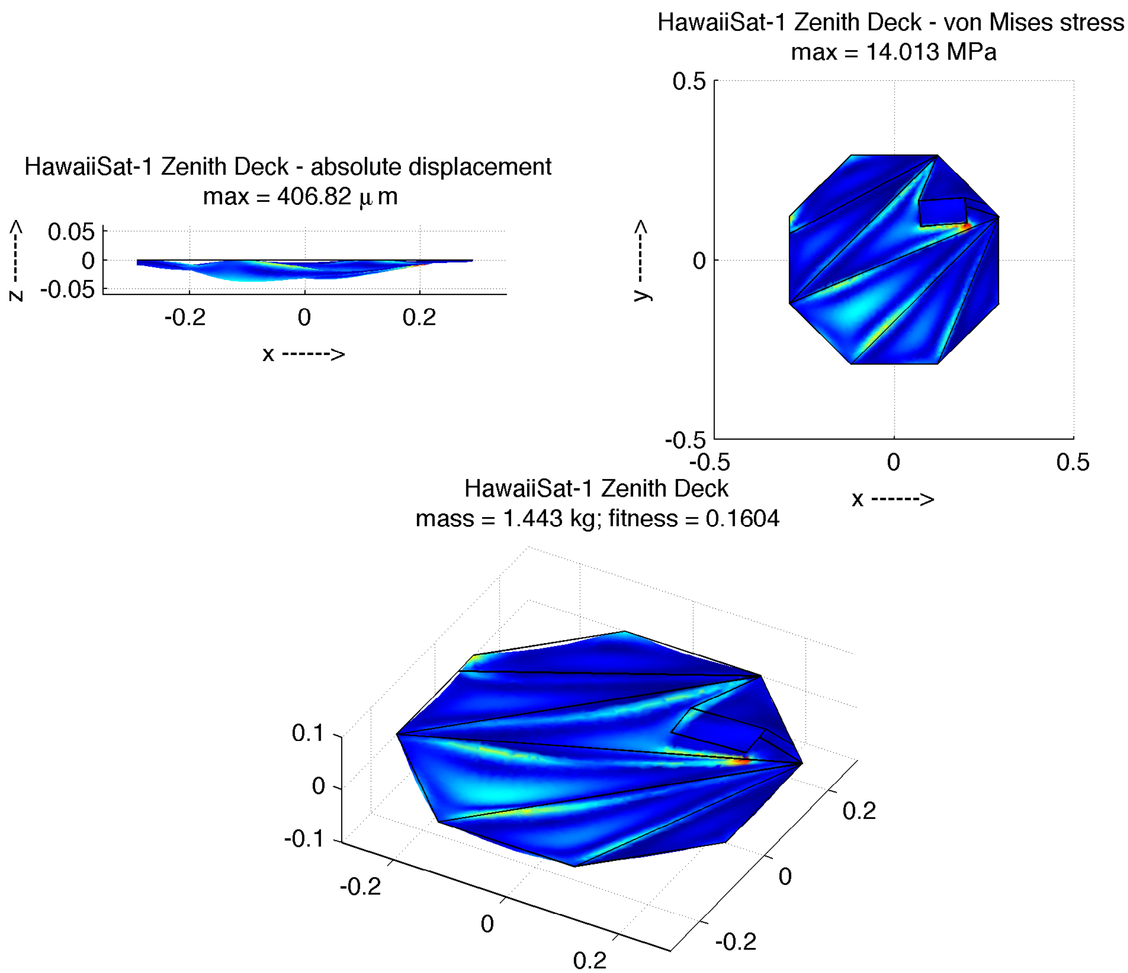


Figure 8: Optimized structure after run #1 with 50 generations and 100 individuals. Final Mass = 1.443 kg, Fitness = 0.1604, and subsystem was free to move.

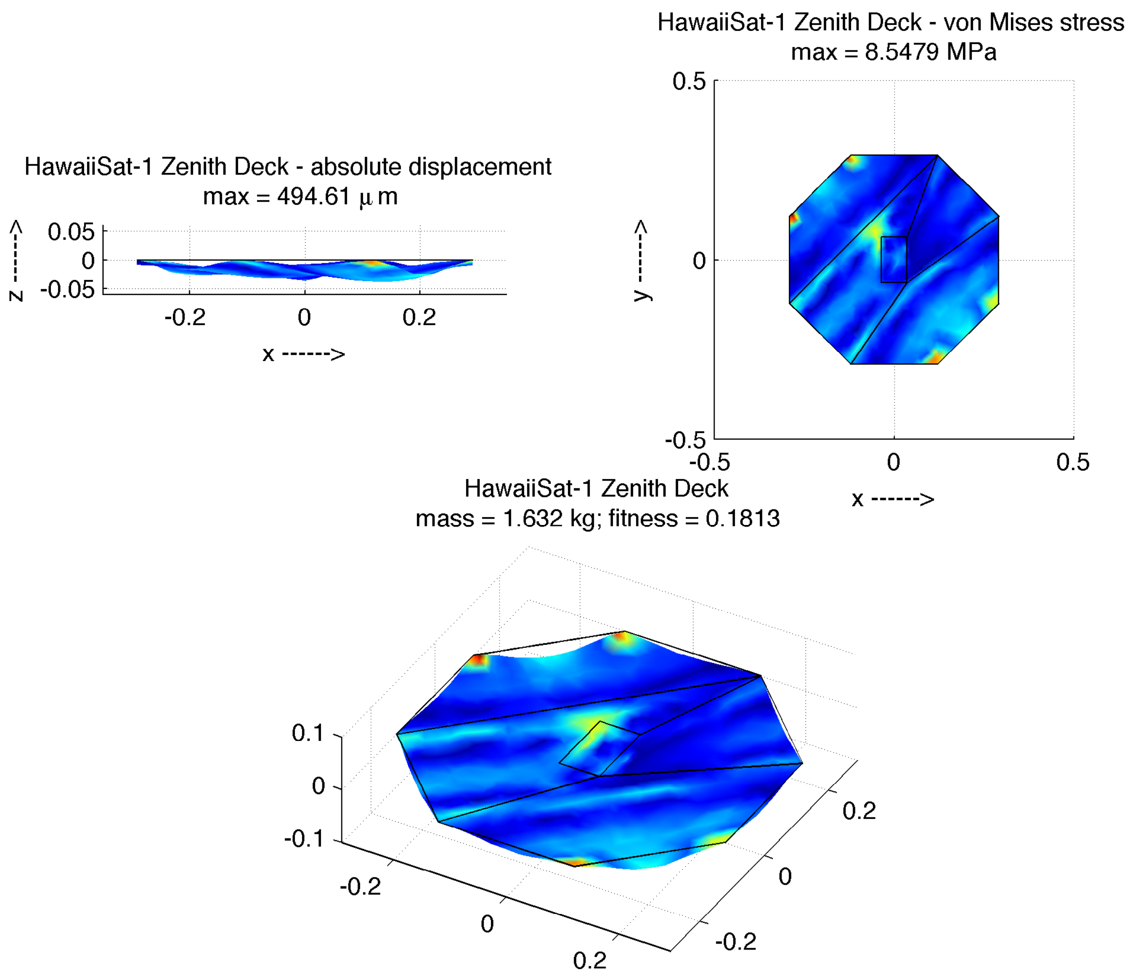


Figure 9: Optimized structure after run #2 with 50 generations and 200 individuals. Final Mass = 1.632 kg, Fitness = 0.1813, and subsystem was fixed.

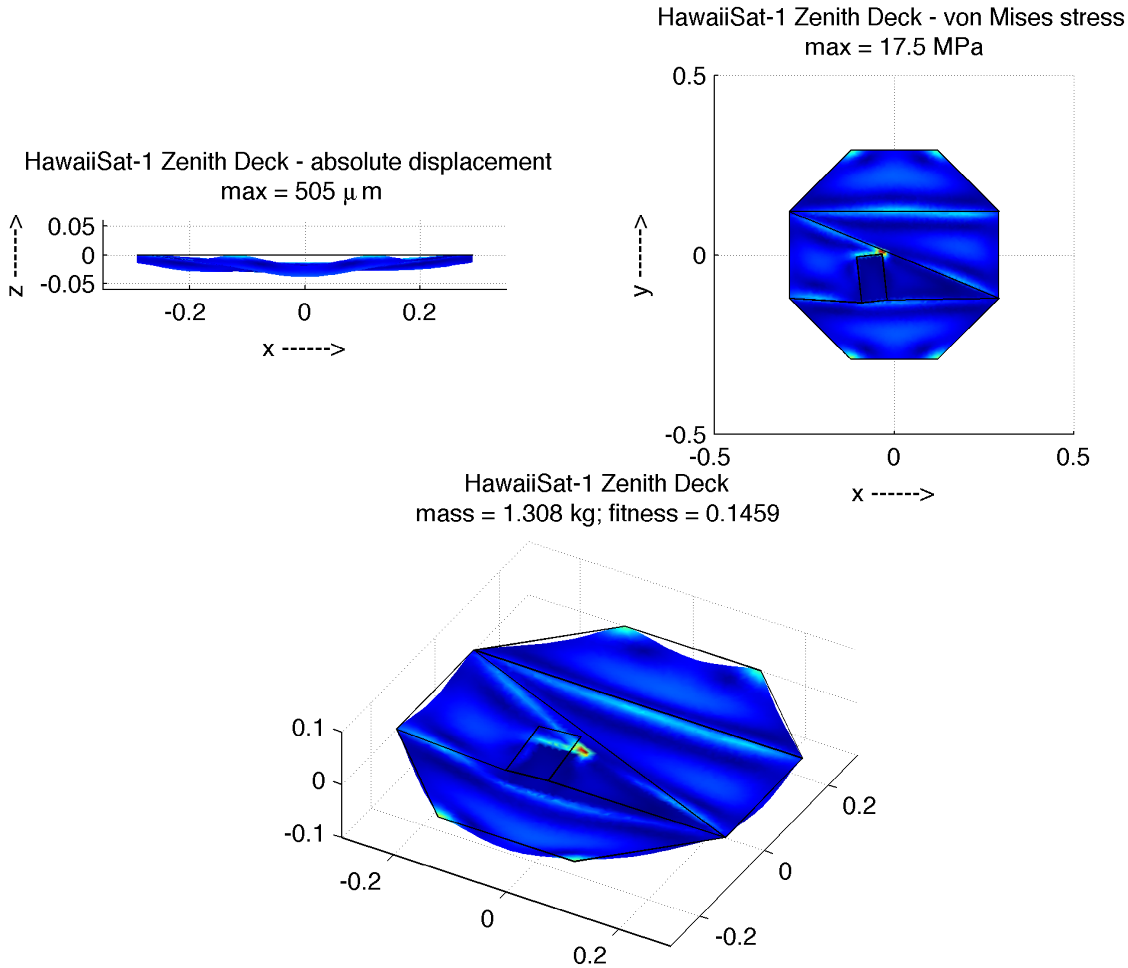


Figure 10: Optimized structure after run #3.1 with 50 generations and 200 individuals. Final Mass = 1.308 kg, Fitness = 0.1459, and subsystem was free to move.

Conference

6. M. A. Nunes, M. H. Kobayashi and R.M. Kolonay (2012) On a cellular division method for layout optimization and sub-system placement 12th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference and 14th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference, Indianapolis, Indiana.
7. B.K. Stanford, P.S. Beran and M.H. Kobayashi (2012) Simultaneous Topology Optimization of Membrane Wings and Their Compliant Flapping Mechanisms AIAA 53rd Structures, Structural Dynamics, and Materials and Co-located Conferences, Honolulu, HI, AIAA-2012-1357.
8. R.M. Kolonay and M.H. Kobayashi (2011) Topology, Shape, and Sizing Optimization of Aircraft Lifting Surfaces Using a Cellular Division Method, International Forum on Aeroelasticity and Structural Dynamics 2011 - IFASD2011 - Paris, France.
9. B.K. Stanford, P.S. Beran and M.H. Kobayashi (2011) Aeroelastic Optimization of Flapping Wing Venation: a Cellular Division Approach, 52nd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Denver, Colorado.
10. R.M. Kolonay and M.H. Kobayashi (2010) Shape and Topology Optimization of Aircraft Lifting Surfaces Using a Cellular Division Method, 13th AIAA/ISSMO Multidisciplinary Analysis Optimization (MAO) Conference, Fort Worth, Texas.

§5. INTERACTIONS

In the period of this grant, the following collaborations took place:

1. McNair Student Achievement Program. "The McNair Student Achievement Program prepares selected University of Hawai'i at Manoa undergraduates to pursue doctoral study. McNair students come from disadvantaged backgrounds and demonstrate strong commitment to academic excellence in science, technology, engineering and math. A cohort of McNair participants each year receives personalized faculty mentoring and other academic services in a culturally and socially supportive environment. As McNair students immerse themselves in research and other scholarly projects, college becomes not only a path to a Ph.D. degree but a stepping stone to making a vital contribution to their respective communities." (Source: http://www.hawaii.edu/diversity/McNair/). Two students, Mr. M. Coloma and Mr. T. Martinez, earned McNair scholarships for Summer Internship in the Summer of 2011 to conduct research within this AFOSR grant.
2. Guest Lecture: Bio-inspired Topology Optimization Method at AVT-182 Workshop on Flight Physics in Micro Air Vehicles and in Nature April 13-15, 2010. Antalya, Turkey. Interaction within RTO AVT-182 NATO project.
3. Guest Lecture: "A Biologically Inspired Topology Optimization Method" at the Istanbul Technical University, April 19, 2010.
4. Hosted Doc.Dr.Melike Nikbay at UHM as Visiting Scholar in the Summer 2012.

§6. HONORS/AWARDS

1. Air Force Research Laboratory/Air Vehicles Directorate (AFRL/RB) 2010 & 2011 Summer Researcher Program Fellowship.